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CDF

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Production of J/ψ from χ_c decays at CDF

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We have measured the fraction of J/ψ originating from χ_c states in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV in four bins of J/ψ P_T . The fraction in the inclusive CDF J/ψ sample with $P_T^{J/\psi} > 4.0$ GeV/c and $|\eta^{J/\psi}| < 0.6$ is $f_\chi^{J/\psi} = 28.3 \pm 1.6(stat) \pm 6.8(syst)\%$. The fraction of J/ψ from χ_c not including contributions from $B \rightarrow J/\psi X$ and $B \rightarrow \chi_c X$ is $f(Nob)_\chi^{J/\psi} = 32.3 \pm 2.0(stat) \pm 8.5(syst)\%$. We have also found that directly produced χ_c 's are produced in the ratio $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1}) + \sigma(\chi_{c2})} = 0.47 \pm 0.08(stat) \pm 0.02(syst.)$

We report a study of the reaction $p\bar{p} \rightarrow \chi_c X \rightarrow J/\psi \gamma X \rightarrow \mu^+ \mu^- \gamma X$ at $\sqrt{s} = 1.8$ TeV. This study yields the fraction of J/ψ from χ_c as a function of $P_T^{J/\psi}$ as well as the ratio of the production cross sections of directly produced χ_{c1} and χ_{c2} states. In $p\bar{p}$ collisions the χ_c mesons are produced directly or from the decay of b hadrons, and according to the current theoretical model for charmonium production [1,2] they are the main source ($> 90\%$) of prompt J/ψ 's, that is of J/ψ 's not coming from b flavored hadrons. The observed yields for the prompt J/ψ 's and $\psi(2S)$'s at CDF are larger than the theoretical expectation by factors of ~ 6 and ~ 50 respectively [3]. The big discrepancy, especially for the $\psi(2S)$ state, has created intense theoretical interest [4–10] and it suggests that there exist other important

mechanisms for production of S wave states at large P_T beyond those that have already been calculated. For the $\psi(2S)$ the only source considered for prompt production is direct production, since higher mass charmonia that can decay to $\psi(2S)$ are not known to exist. Therefore it is important to account for all charmonium states produced at CDF and understand whether the large disagreement with theory is confined to the $\psi(2S)$ production or an excess of direct production shows up for the J/ψ as well.

Our data have been taken with the CDF detector which has been described in detail elsewhere [11,12]. The components relevant to this analysis are briefly described here. The central tracking chamber (CTC) is in a 1.4 T axial magnetic field and consists of nine superlayers, four of which give stereo information. A Silicon Vertex Detector (SVX) provides high-resolution $r - \phi$ tracking information near the interaction region. The SVX detector covers the luminous region of $|z| < 26$ cm along the beam line and consists of four layers of DC coupled, single sided, silicon microstrip detectors with an innermost radius of 2.9 cm. The momentum resolution for tracks detected by both the CTC and SVX systems is $\delta P_t/P_t = \sqrt{(0.0009P_t)^2 + (0.0066)^2}$. Surrounding the CTC are the central electromagnetic calorimeter (CEM), the central electromagnetic strip chambers (CES) and the central hadronic calorimeter (CHA) providing five absorption lengths of material before the Central Muon Chambers (CMU). The CES chambers are located at a depth of six radiation lengths in the electromagnetic calorimeter and have a position resolution of approximately 1 cm. The CMU chambers, at a radius of 3.5 m from the beam axis, cover the pseudorapidity region $|\eta| < 0.6$. These chambers are complemented by the central muon upgrade

system (CMP) which consists of four layers of drift tubes behind 2 feet of steel. Use of the CMP considerably reduces hadronic punch-through backgrounds to the muon signal.

At CDF we reconstruct the χ_c mesons through the decay chain $\chi_c \rightarrow J/\psi \gamma$, $J/\psi \rightarrow \mu^+ \mu^-$ and we detect the photon by using either calorimeter or tracking information.

By using a data sample of $\sim 18 \text{ pb}^{-1}$ we measured the fraction of J/ψ 's from χ_c 's by detecting the photon with the calorimeter method. We first identified the J/ψ mesons by requiring two oppositely charged muon candidates, where the P_T of both muons was required to be greater than 2.0 GeV/c and at least one muon had to have P_T greater than 2.8 GeV/c. Finally, we selected muon pairs with $P_T > 4.0 \text{ GeV/c}$ and pseudorapidity in the range $|\eta| < 0.6$ and we found $32,642 \pm 181 \text{ } J/\psi$ candidate events. The photon candidates were selected by demanding an electromagnetic energy deposition with at least 1 GeV at a CEM calorimeter tower and a cluster in the CES chambers. We required as well that no track is hitting the tower corresponding to the photon candidate. The energy and direction of the photon candidate were combined with the muon momenta to determine the invariant mass of the $\mu^+ \mu^- \gamma$ system and we formed the mass difference distribution, $\Delta M = M(\mu^+ \mu^- \gamma) - M(\mu^+ \mu^-)$, which is shown in Fig. 1. A clear χ_c signal of $1,230 \pm 71$ events is present near $\Delta M = 0.4 \text{ GeV}$ but the individual χ_c angular momentum states are not resolved.

We obtained the shape of the background with a Monte Carlo method that used as input real $J/\psi \rightarrow \mu^+ \mu^-$ events containing charged tracks other than the two muons. Each charged track in the event was assumed to be a π^0 , η or K_s in ratios predicted

by the measured K^\pm/π^\pm and η/π^0 ratios and isospin symmetry. The particles were decayed and the resulting photons were simulated through the detector. Applying the χ_c reconstruction to this event gave a distribution that is our model for the shape of the background. To test this model we compared the distribution obtained in this way with the one directly obtained from the data for dimuon pairs in the sidebands of the J/ψ peak where there is no χ_c signal and we found good agreement.

The fraction of J/ψ from χ_c was calculated according to the equation

$$f_\chi^{J/\psi} = \frac{N^{\chi_c}}{N^{J/\psi} \cdot A_{J/\psi}^\gamma \cdot \epsilon_{NoTrack}^\gamma \cdot \epsilon_{Envir}^\gamma}$$

where N^{χ_c} is the number of reconstructed χ_c 's, $N^{J/\psi}$ is the number of reconstructed J/ψ 's, $A_{J/\psi}^\gamma$ is the photon acceptance, $\epsilon_{NoTrack}^\gamma$ is the efficiency of the no track cut and ϵ_{Envir}^γ is the efficiency to reconstruct the photon in the presence of additional (non-photon) energy deposited in the calorimeter.

The photon acceptance, $A_{J/\psi}^\gamma$, is the probability to reconstruct the photon once the J/ψ is found. It was assumed to be the convolution of the probability that the photon lands in the fiducial volume of the calorimeter and the strip chambers after the J/ψ is found (A_{fid}^γ), and the efficiency for reconstructing the photon when it is in our fiducial volume (A_{rec}^γ). We determined A_{fid}^γ by using a Monte Carlo simulation. We generated χ_c 's with a flat pseudorapidity spectrum and a P_T distribution parametrized by a power law function and we generated the $\chi_c \rightarrow J/\psi\gamma$ decay with a uniform angular distribution in the χ_c rest frame. We then propagated the decay particles through the detector by simulating the CMU chambers, the CES chambers and the CEM calorimeter. We have also applied the trigger simulation to these Monte Carlo

events. The A_{rec}^γ efficiency was obtained by examining a sample of electrons from conversion photons in which one of the electrons was selected using only tracking information. We calculated the electron efficiency from the number of electron tracks that passed the CEM and CES criteria for photons and we converted it to a photon efficiency by correcting for the known differences in detector response between photons and electrons.

To study the effect of the no track cut and the effect of additional (non-photon) energy deposited in the calorimeter, we used a sample of χ_c 's reconstructed using a method based purely on tracking, requiring that the photon has converted in an electron positron pair. From about 70 events reconstructed in this way we concluded that the no track cut does not significantly affect our ability to find the photon with our calorimeter based selection. The absence of significant activity in the vicinity of the χ_c is shown in Figures 2 A) and B) where we show the multiplicity of tracks pointing to the photon tower and the electromagnetic energy in the same tower when there are no tracks pointing to it. We found that $\epsilon_{NoTrack}^\gamma = (89 \pm_{-5}^{+4})\%$ and that $\epsilon_{Envir}^\gamma = (94 \pm 7)\%$.

Systematic uncertainties in the measurement of $f_\chi^{J/\psi}$ arise from the χ_c production and decay model (11%), the background determination (6%), variations in the photon fiducial volume (10%), the difference between the electron and photon detector response (16%) and the photon reconstruction efficiencies (8.5%).

We found that the fraction, $f_\chi^{J/\psi}$, of inclusive J/ψ 's with $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$ coming from χ_c 's is $f_\chi^{J/\psi} = 28.3 \pm 1.6(stat) \pm 6.8(syst)\%$. This fraction includes a contribution from $B \rightarrow J/\psi X$ and $B \rightarrow \chi_c X$ decays. We removed this

contribution by using the cross section of J/ψ from b 's measured by CDF [3] and branching ratios of B mesons to charmonium states measured by CLEO [13]. We have found that the fraction of J/ψ 's with $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$ coming from χ_c 's and not including contributions from $B \rightarrow J/\psi X$ and $B \rightarrow \chi_c X$ decays is $f(Nob)_\chi^{J/\psi} = 32.3 \pm 2.0(stat) \pm 8.5(syst)\%$. We find that the production from χ_c 's is not the dominant production mechanism of prompt J/ψ 's, in disagreement with current theoretical predictions. In Fig. 3 we present the fraction $f(Nob)_\chi^{J/\psi}$ as a function of $P_T^{J/\psi}$. To obtain the cross section of J/ψ 's from χ_c 's we parametrized the fraction $f(Nob)_\chi^{J/\psi}$ as function of $P_T^{J/\psi}$ with an exponential function and we multiplied this fraction parametrization with our J/ψ cross section from Ref. [3]. The result is shown in Fig. 4. The curves are theoretical predictions from Ref. [2,14]. The production cross section of J/ψ from χ_c is in reasonable agreement with the theoretical calculation while the direct J/ψ production cross section is a large factor above the prediction.

By using a data sample of 75 pb^{-1} we reconstructed a χ_c signal through the detection of conversion photons and we measured the ratio of production cross sections for the individual χ_{c1} and χ_{c2} states. With this method the photon reconstruction uses only tracking information greatly improving the χ_c mass resolution. We required two oppositely charged muon candidates, where the P_T of both muons was greater than 1.8 GeV/c and at least one muon had to have P_T greater than 2.8 GeV/c. We selected muon pairs with $P_T > 6.0$ GeV/c and pseudorapidity in the range $|\eta| < 0.5$ and required a conversion vertex separated from the primary interaction vertex by more than 1 cm in the transverse plane. We requested as well the momentum of the

conversion pair to be greater than 1 GeV/c. To select prompt χ_c candidates we used muon pairs reconstructed in the SVX and imposed the requirement that the proper lifetime, λ , of the $J/\psi - \gamma$ system is less than 100 μm . We have 46.4 ± 7.2 prompt χ_{c1} 's and 23.2 ± 6.4 prompt χ_{c2} 's (see Fig. 5). These rates, with a small acceptance correction and the known decay branching ratios of χ_{c1} and χ_{c2} to $J/\psi\gamma$ were used to obtain the relative production cross sections of χ_{c1} and χ_{c2} . We have measured

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1}) + \sigma(\chi_{c2})} = 0.47 \pm 0.08(\text{stat}) \pm 0.02(\text{syst.}).$$

In conclusion, we have measured the fraction of J/ψ 's from χ_c 's and we found that the majority of prompt J/ψ 's do not come from χ_c 's, contrary to the theoretical predictions. We also found that the color singlet QCD model of charmonium production fails to describe direct production, both for the J/ψ and $\psi(2S)$ states by about the same large amount.

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Figure Captions

- 1) The mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region. The points represent the data. The shaded histogram is the background shape predicted by our background Monte Carlo. The solid line is the fit to the data of a gaussian signal plus the background histogram. Calorimeter information is used for the detection of the photon, and $P_T^\gamma > 1 \text{ GeV}/c$.
- 2) Characteristics of the χ_{c1} events obtained employing the photon reconstruction through its conversion pair. A) Multiplicity of non muon tracks pointing to the tower identified by the photon. B) Electromagnetic energy in the tower identified by the photon when no tracks point to it.
- 3) The fraction of J/ψ from χ_c as a function of $P_T^{J/\psi}$ with the contribution from b 's removed. Calorimeter information is used for the detection of the photon, and $P_T^\gamma > 1 \text{ GeV}/c$.
- 4) Differential cross sections of prompt J/ψ as a function of $P_T^{J/\psi}$ with the contribution from b 's removed.
- 5) The mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region and for $P_T^\gamma > 1 \text{ GeV}/c$, where tracking information is used for the detection of the photon.

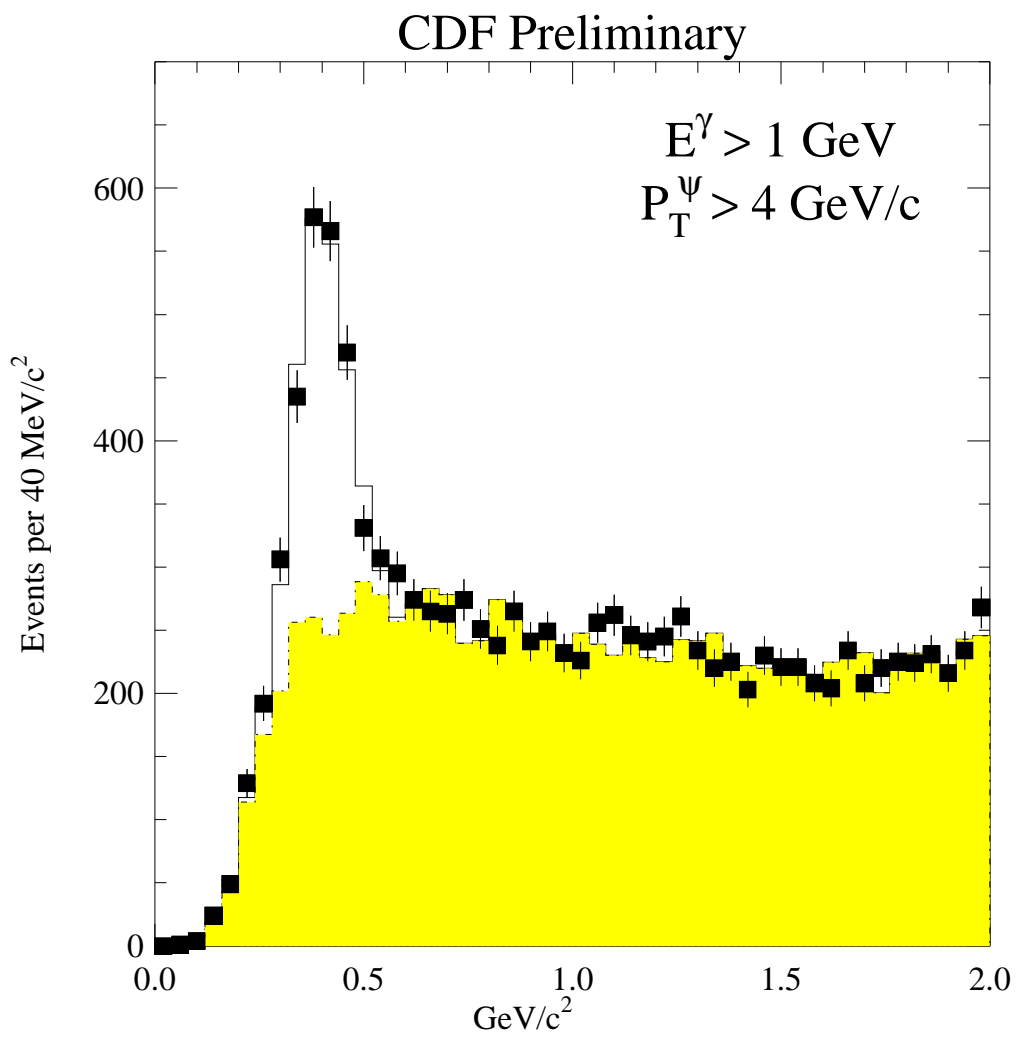


FIG. 1.

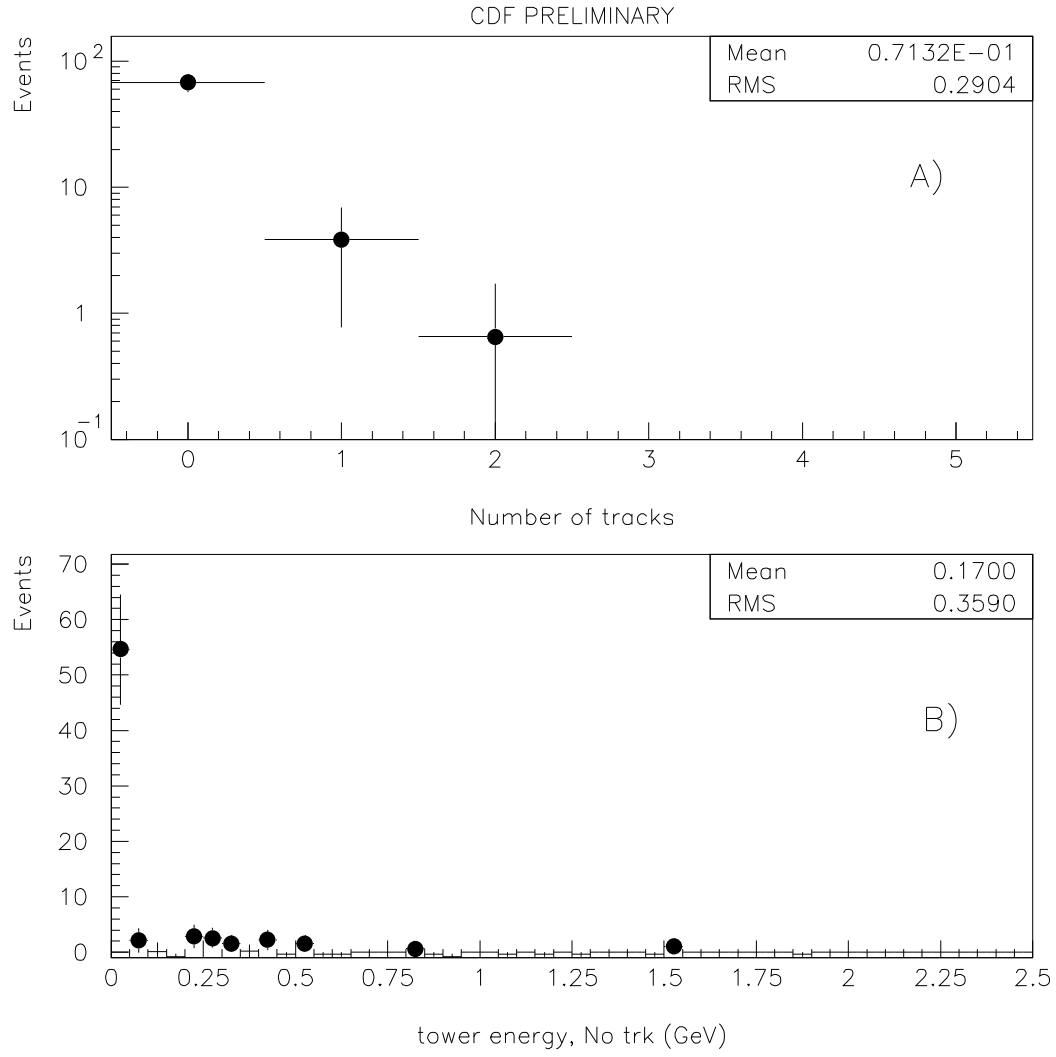


FIG. 2.

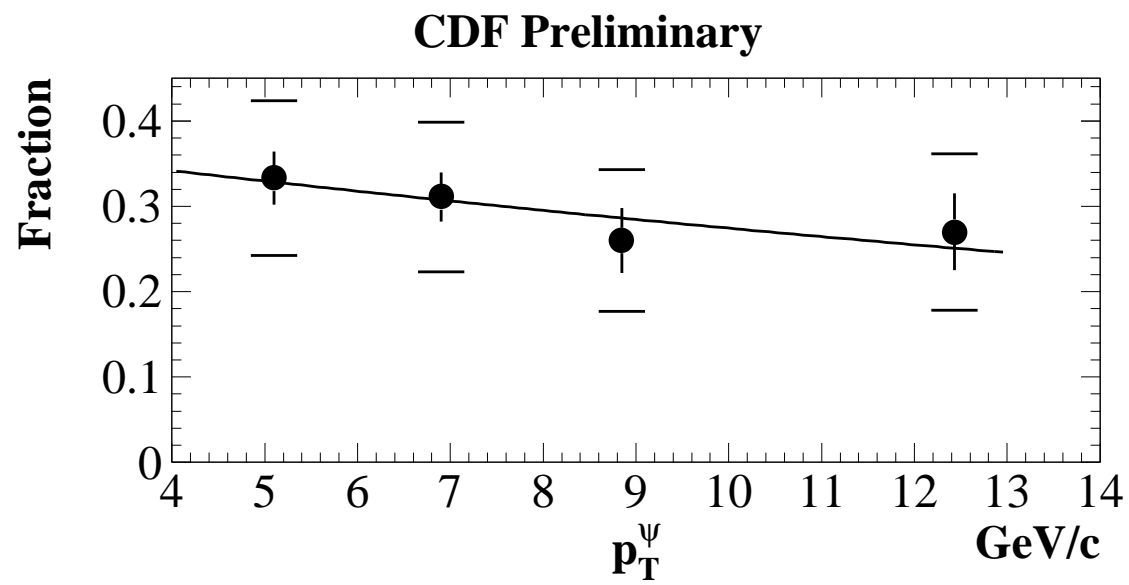


FIG. 3.

CDF PRELIMINARY

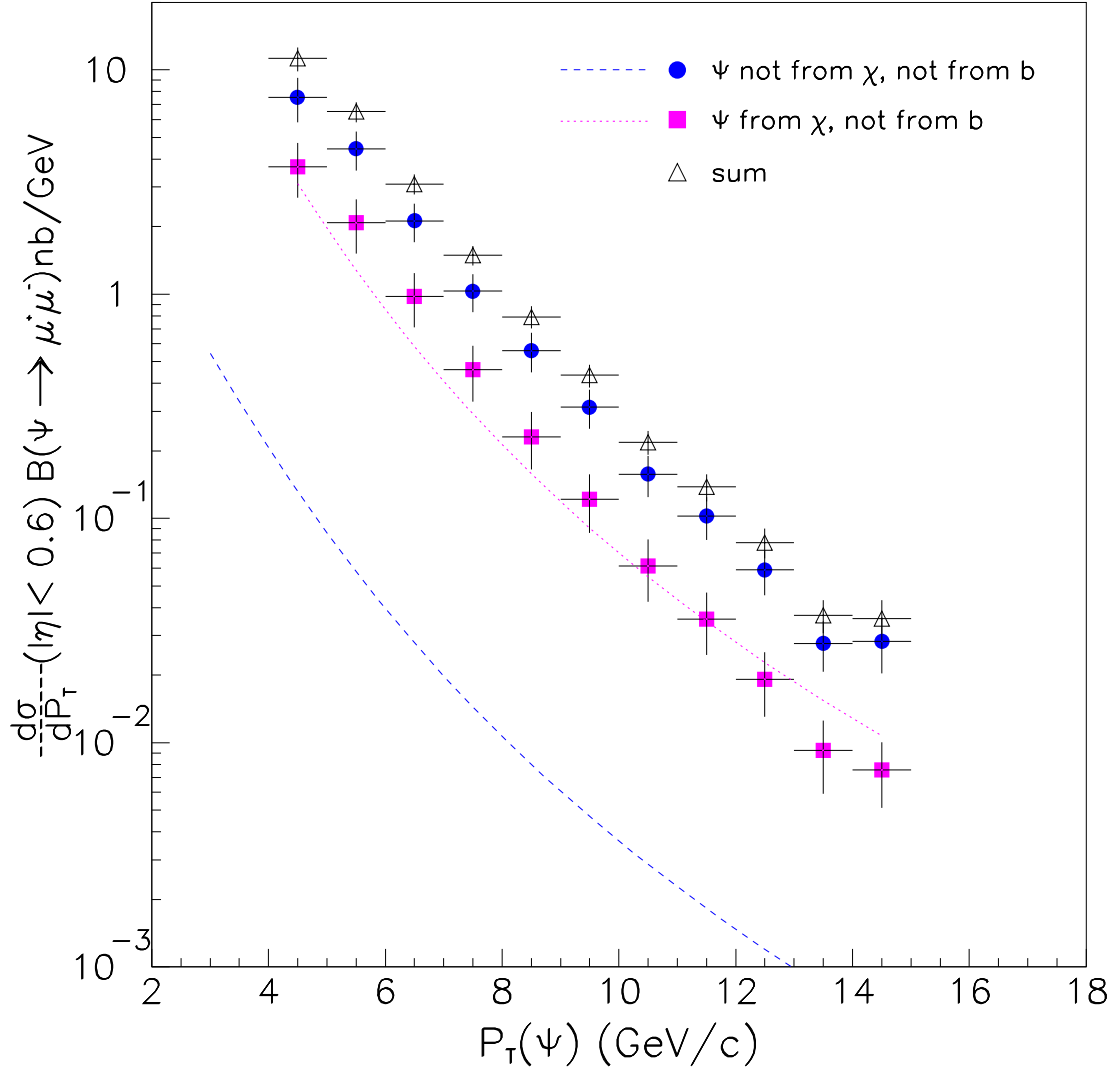


FIG. 4.

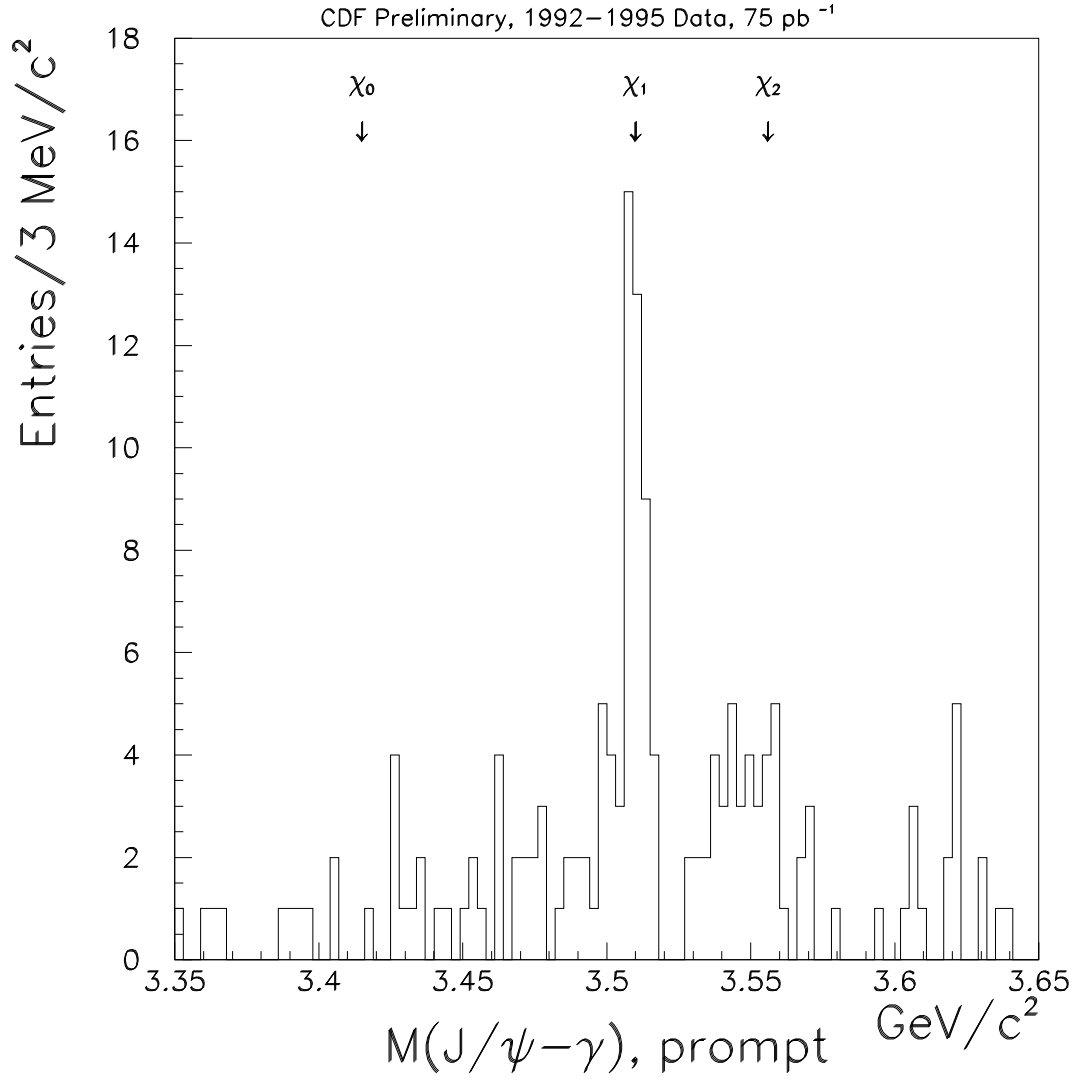


FIG. 5.